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Eta Mesons in Nuclei

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INTRODUCTION

To date, the most studied meson-nucleus strong interactions are those induced by pions. The study of these interactions has provided us valuable information concerning the propagation of mesons in general, and pions in particular, in a many-body nuclear environment; information that will greatly facilitate the study of other meson-nucleus systems.

The study of η mesons in nuclei is of fundamental interest. This is because the structure of the η meson is still not fully understood. The simple SU(6) quark model cannot account for the mass difference between η and η' mesons. Studies of eta-nucleon interactions will provide useful information that might shed light on the structure of η. Because it is nearly impossible to produce an η beam, the nucleus is the only laboratory for η-nucleon physics.

The threshold for the reaction $\pi^- p \to \eta n$ on a free nucleon is at pion kinetic energy $T_\pi \simeq 561$ MeV or total c.m. energy $\sqrt{s} = 1488$ MeV. The cross section rises rapidly with pion energy and reaches a maximum (~2.5 mb) at $T_\pi \simeq 661$ MeV ($\sqrt{s} = 1550$ MeV); an energy that is only slightly higher than the limit of existing pion factories. The threshold for the reaction $pp \to pp\eta$ is at proton kinetic energy $T_p \simeq 1.26$ GeV. For simple kinematical reasons, the threshold for nuclear (π,η) and $(p,p\eta)$ reactions are much lower. Because an understanding of the $NN \to NN\eta$ reactions depends on an understanding of $\pi N \to \eta N$ reactions, in my opinion, the use of a high-intensity pion beam with energies between 0.6 and 1.0 GeV represents a logical first choice for the intial-stage investigation of η's in nuclei.

ETA-NUCLEON INTERACTION

For πN c.m. energies between 1470 and 1600 MeV, there are only three important reaction channels: πN elastic scattering, $\pi N \to \pi\pi N$, and $\pi N \to \eta N$. Bhalerao and Liu have developed a coupled-channel isobar model to study simultaneously all three reaction channels.[1]

They have found that in this energy region only one isobar has to be considered for each given meson-nucleon partial-wave amplitude; they are N*(1535) for the s-wave, N*(1440) for the p-wave, and N*(1520) for the d-wave amplitude. The coupled-channel analysis gives the following ratios between various coupling constants involving the N*(1535):

$$g_{\pi NN^*}/g_{\pi N\Delta} = 0.55; \quad (1a)$$

and

$$g_{\pi NN^*}/g_{\eta NN^*} = 1.69. \quad (1b)$$

The same analysis also gives

$$g_{\pi N\Delta}/g_{\pi\Delta\Delta} = 1.9. \quad (1c)$$

which is very close to the value (~2.1) given by the quark model. Because[2]

$$g_{\pi NN}/g_{\pi N\Delta} = 0.59 \quad (2a)$$

and

$$g_{\pi NN}/g_{\eta NN} = 1.71, \quad (2b)$$

we deduce from Eqs.(1a) and (2a) that

$$g_{\pi NN^*} \simeq g_{\pi NN}. \quad (3a)$$

Using Eqs.(1b),(2b), and (3a), we further deduce that

$$g_{\eta NN^*} \simeq g_{\eta NN}. \quad (3b)$$

It is interesting to see to what extent these ratios would be modified in nuclear reactions where the formation of an on-shell N*(1535) is energetically possible.

THEORY OF ETA-MESIC NUCLEI

Various analyses of the $\pi N \to \eta N$ reaction indicate that the low-energy ηN interaction is attractive.[1,3] The coupled-channel isobar model of Ref.1 is particularly suitable for calculating ηN interactions in a nucleus because it contains strong-interaction form factors and satisfies off-shell unitarity. For this reason, I shall only discuss the calculations based on that model.

In the isobar model, the radial part of the ηN scattering amplitude is given by[1]

$$\langle p'|T^{\alpha}_{\eta N,\eta N}(\sqrt{s})|p\rangle = \frac{g^2_{\eta N\alpha} v_{\eta N\alpha}(p',\Lambda_{\eta N\alpha}) v_{\eta N\alpha}(p,\Lambda_{\eta N\alpha})}{\sqrt{s}-m^{\alpha}_{B}-\Sigma^{\alpha}_{\pi\pi}(\sqrt{s})-\Sigma^{\alpha}_{\pi}(\sqrt{s})-\Sigma^{\alpha}_{\eta}(\sqrt{s})} . \qquad (4)$$

In Eq.(4), v is the strong-interaction form factor. The g and Λ are, respectively, the coupling constant and range parameter. The m^{α}_{B} is the bare mass of the isobar (denoted α). The $\Sigma^{\alpha}_{\pi\pi}$, Σ^{α}_{π}, and Σ^{α}_{η} are the self-energies of α, which arise from the coupling of the isobar to the $\pi\pi N$, πN, and ηN channels, respectively. The sum of the imaginary parts of Σ gives the width of the isobar Γ_{α}, while the sum of the bare mass and the real parts of Σ gives the physical isobar mass m_{α}, i.e.

$$m^{\alpha}_{B} + \Sigma^{\alpha}_{\pi\pi} + \Sigma^{\alpha}_{\pi} + \Sigma^{\alpha}_{\eta} = m_{\alpha}(\sqrt{s})-i\Gamma_{\alpha}(\sqrt{s})/2 . \qquad (5)$$

We note that m_{α} and Γ_{α} are energy-dependent. The m_{α}, g, and Λ of the coupled-channel theory of Ref.1 are determined from fitting only the πN phase shifts. The theory is able to make a good prediction for the $\pi^- p \to \eta n$ differential cross sections. It also gives an ηN scattering length a_0=0.28 +i 0.19 fm, corresponding to an attractive s-wave ηN interaction.

Haider and Liu have constructed a first-order optical potential for η-nucleus scattering,[4] using the ηN interaction of Ref.1. They have noted: (a) after including the s-, p-, and d-wave ηN interactions, the η-nucleus interaction remains attractive at low energies; (b) although the strength of the ηN attraction is not sufficient to bind the η to a single nucleon, it can bind an η into a nuclear orbital in a nucleus having a mass number A > 10. In order to see how the size of a nucleus can help develop an η-nucleus bound state, let us examine the case with uniform nuclear density. In this latter case, the condition for the nucleus to have one s-wave bound state is simply[4]

$$9X > \mathrm{Re}(a_o) > X, \tag{6}$$

where a_o is the ηN scattering length and $X = \pi^2 R A^{-1}(1+m_\eta/m_N)^{-1}/12$ with m_η, m_N, and R being, respectively, the η mass, the nucleon mass, and the nuclear radius. The depth of the η-nucleus optical potential well is

$$V = -197.3 \times (3Aa_o/2R^3)(1+m_\eta/m_N)(m_\eta+m_A)/(m_\eta m_A) \quad [\mathrm{MeV}], \tag{7}$$

where $m_A = Am_N$ is the mass of the nucleus, and the unit of the masses is fm^{-1}. In the following table, we give the bound-state conditions and the potential wells calculated with the $a_o = 0.28 + i\,0.19$ fm.

Nucleus	V [MeV]	9X [fm]	X [fm]
p	-5.5-i 3.7	11	1.23
^{6}Li	-8.9-i 6.0	2.5	0.26
^{12}C	-17-i 12	1.3	0.14
^{16}O	-19-i 13	1.0	0.11
^{40}Ca	-20-i 14	0.53	0.059
^{90}Zr	-24-i 16	0.29	0.032
^{208}Pb	-29-i 20	0.15	0.017

Using Eq.(6), we see that there is one s-wave η-nucleus bound state for 10<A<90 and two for A>90. This qualitative result has been confirmed by our detailed calculations that make use of realistic nuclear densities, and full ηN interactions. The calculated binding energies are shown in Fig.1. The calculated widths of ground-state η-mesic nuclei range from ~7 MeV in ^{12}C, ~10 MeV in ^{16}O, to 20 MeV in ^{208}Pb (Ref.1), which are compatible with the imaginary parts of the equivalent square-well potential in the table. We emphasize that the coupled-channel analysis of Ref.1 fits the S11 πN phase shifts. Consequently, the a_o used in our analysis is consistent with the decay width (~100 MeV) of the N*(1535) in free space. We thus conclude that once a bound state is formed, its width is mainly determined by the equivalent potential well and not by the free-space width of the elementary meson-nucleon resonance. In addition, because the imaginary part of Σ_η vanishes at the threshold energy, the actual imaginary part of the η optical potential is much smaller than that implied by the use of a_0 and Eq.(7).

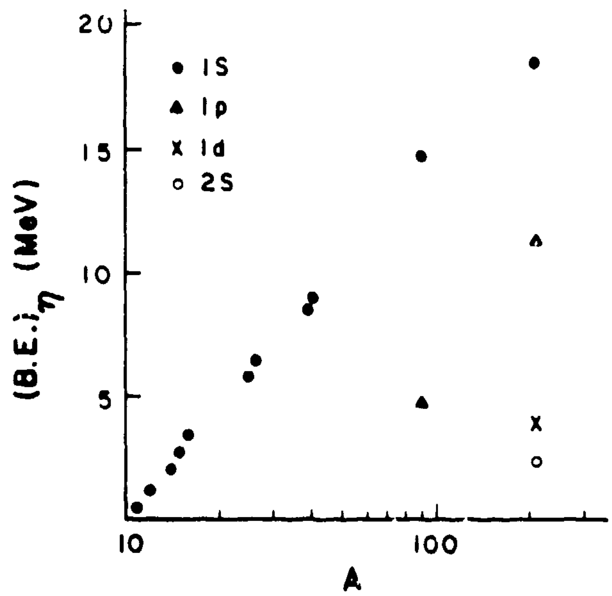

Fig.1. Calculated η binding energies.

The η-nucleus interaction depends nonlinearly on $g^2_{\eta NN*}$ because in Eq.(4) both the numerator and the self-energy Σ_η in the denominator are proportional to the $g^2_{\eta NN*}$. As a result of this dependence, the η-nucleus bound state can only exist for limited values of $g_{\eta NN*}$. In Fig.2, I present the calculated ηN scattering length a_0 and the corresponding η binding energy B and half-width $\Gamma/2$ of the η-mesic nuclear ground state of $^{16}_{\eta}O$ as functions of $g_{\eta NN*(1535)}$. The value of g determined in Ref.1 is 0.77 (indicated by a vertical arrow). It gives $Re(a_0)$=0.28 fm, B=2.4 MeV, and $\Gamma/2$=5.2 MeV. The B and Γ increase rapidly with g. But, the bound state ceases to exist for g>0.9 because the nonlinear relation between ηN scattering amplitude and g^2 causes $Re(a_0)$, and hence, the η-nucleus attraction to decrease for g>0.85. Therefore, bound state can only exist for g between 0.7 and 0.9. This narrow band of allowed values of g provides the possibility to extract quite accurately the $\eta NN*$ coupling constant from experiments.

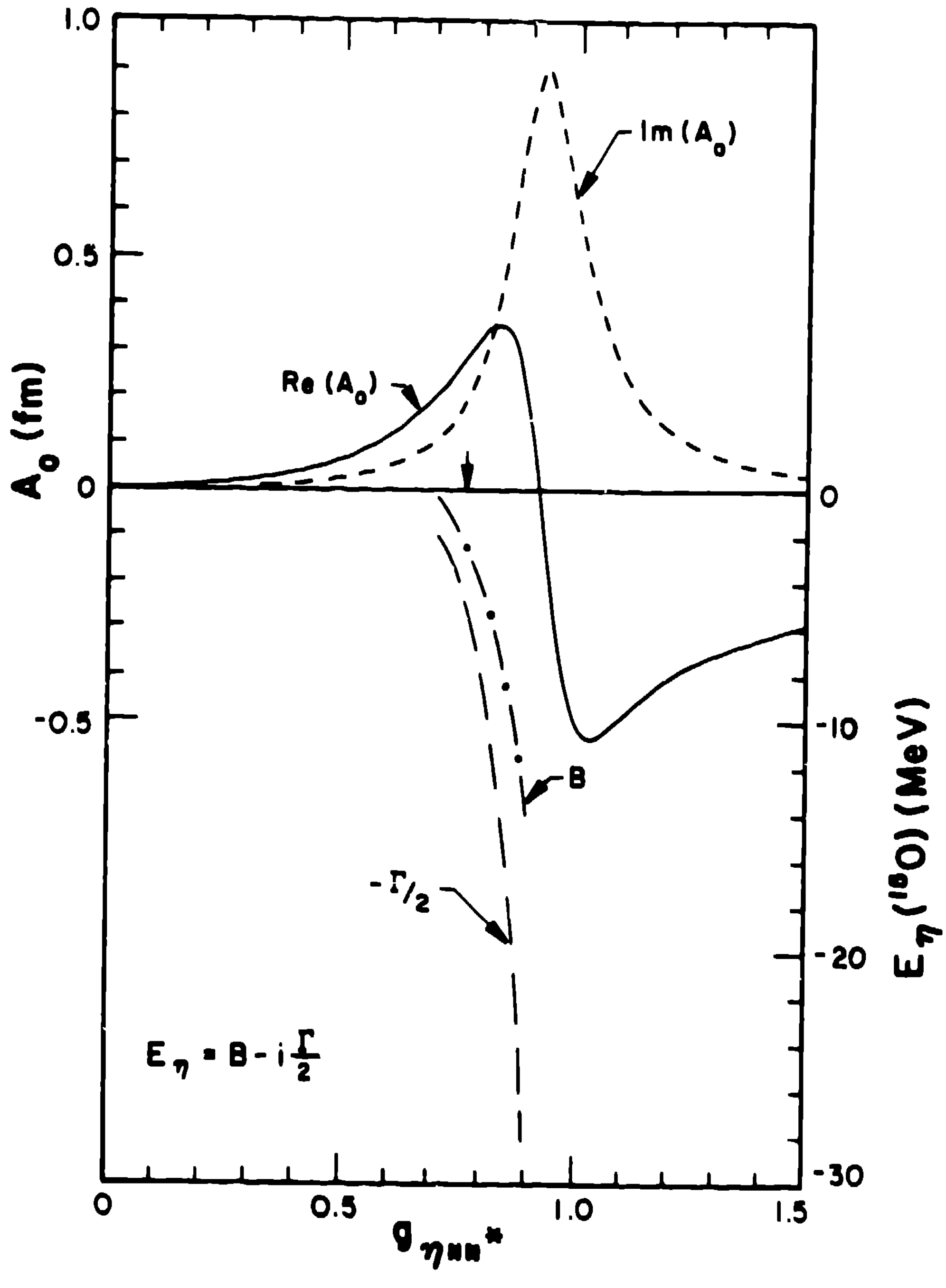

Fig.2. The ηN scattering length a_0, the η binding energy B and half-width $\Gamma/2$ of $^{15}_{\eta}O$(gr.st.) as functions of $g_{\eta NN^*}$.

HIGHER-ORDER SPREADING WIDTHS OF ETA-MESIC NUCLEAR STATES

Let us briefly examine effects of true η absorption on the width of an eta-mesic nuclear state. For this purpose, it is useful to compare pion absorption and eta absorption. Diagrams for these absorption processes are shown in Fig.3.

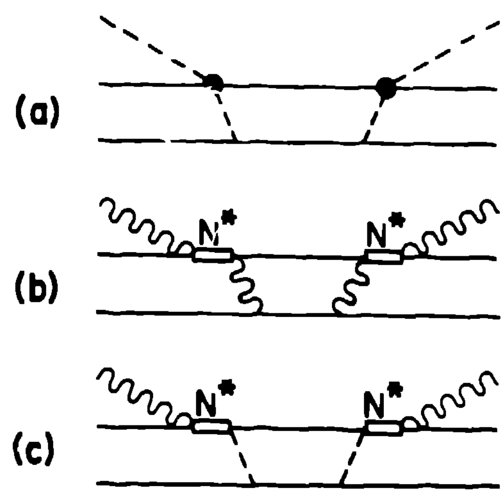

Fig.3. Contributions to the pion-nucleus or η-nucleus optical potential from two-nucleon meson absorption; (a) pion absorption; (b) η absorption; and (c) "indirect" η absorption. The wavy, dashed, and solid lines denote, respectively, the eta, pion, and nucleon.

Figure 3(b) corresponds to an η absorption after ηN scattering. Figure 3(c) corresponds to an "indirect" η absorption in the sense that the η is first converted to a high-energy ($\sim 3M_\pi$) pion that is subsequently absorbed. Detailed microscopic calculations of these diagrams are in progress and will be reported elsewhere. However, it is possible to give an order-of-magnitude estimate of the effect of η absorption. The imaginary part of the second-order η optical potential associated with s-wave η absorption, due mainly to Fig.3(b), is given by

$$W = -4\pi \, \mathrm{Im}(B_0^\eta) \, [\rho(0)]^2, \qquad (8)$$

where B_0^{η} is the absorption strength for η and may be estimated from scaling the s-wave pion absorption strength B_0^{π} with the relation

$$Im(B_0^{\eta})=(g_{\eta NN^*}/g_{\pi NN})^4(g_{\eta NN}/g_{\pi NN})^2 \ Im(B_0^{\pi}). \qquad (9)$$

Here $Im(B_0^{\pi})=0.04\ M_{\pi}^{-4}$ is the pion absorption strength. Using $\rho(0)=0.17\ fm^{-3}$ and Eqs.(2) and (3), one obtains $|W|<1$ MeV. A similar estimate of the diagram in Fig.3(c) again leads to a $|W|$ of ~1 MeV. Thus, at the threshold, the imaginary part of η-nucleus optical potential due to η absorption by two nucleons is much smaller than that due to one-nucleon processes.

EXPERIMENTAL SEARCH

An experiment was performed at the AGS of Brookhaven National Laboratory.[5] The reaction used was

$$\pi^+ + {}^{Z}A \rightarrow p + [\eta + {}^{Z}(A-1)] = p + {}^{\eta}_{Z}(A-1).$$

If an η-mesic nucleus is formed, then a nearly monoenergetic peak will be seen in the outgoing proton spectrum at a well-defined energy. In particular, the peak that corresponds to the formation of a bound state of η, after having ejected a least-bound neutron, will be situated outside the kinematical limit of quasi-free η production and by a distance equal to the binding energy of the η. In Fig.4, I show a predicted proton spectrum for the ${}^{16}O(\pi^+,p)X$ reaction at a pion momentum of 740 MeV/c, where the abscissa is converted to the binding energy of η.(Ref.6.) Because the width of ${}^{15}_{\eta}O$ is ~10 MeV, the two peaks associated with the ejection of $1p_{1/2}$ and $1p_{3/2}$ neutrons cannot be separated in our calculations. The actual experiment was performed with 800-MeV/c incident π^+ on lithium, carbon, and oxygen. Data analysis is still in progress.

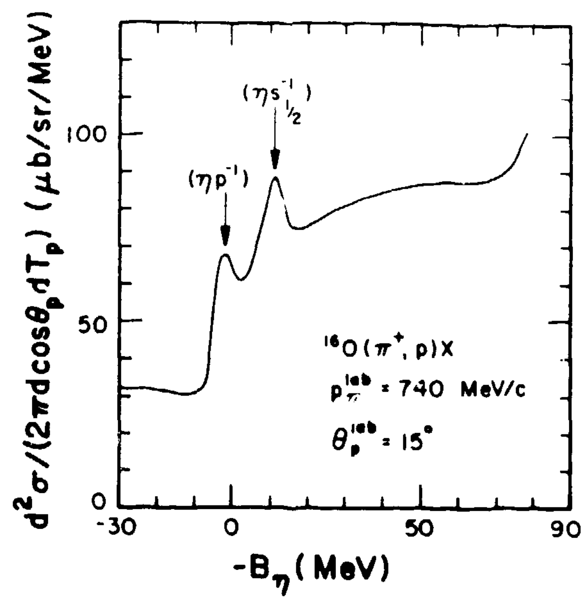

Fig.4. Calculated proton spectrum.

A second experiment will be carried out at LAMPF.[7] In this experiment one will detect in coincidence the ejected fast proton, and the decay product of the η-mesic nucleus, using a BGO ball. The corresponding reaction is

$$\pi^+ + {}^{Z}_{\eta}A \rightarrow p + {}^{Z}_{\eta}(A-1) \rightarrow p + \pi^0 + p + X,$$

where X denotes all the undetected particles. The π^0 and the second proton are coming from the elementary process $\eta^{bound}+p\rightarrow\pi^0+p$. This triple coincidence measurement should greatly reduce the background events and provide information on the decay of an η-mesic nucleus.

OTHER EXPERIMENTAL POSSIBILITIES

Because the η meson can also be produced in high-energy pp collisions, it will be interesting to look for clues of η-mesic nucleus formation in proton-nucleus reactions. Because small η momenta are favorable to such formation, it is preferable that one works in an energy region where this kinematics can be realized. In Figs. 5 and 6, I present plots indicating the minimum η momentum that will be produced in various nuclear reactions.

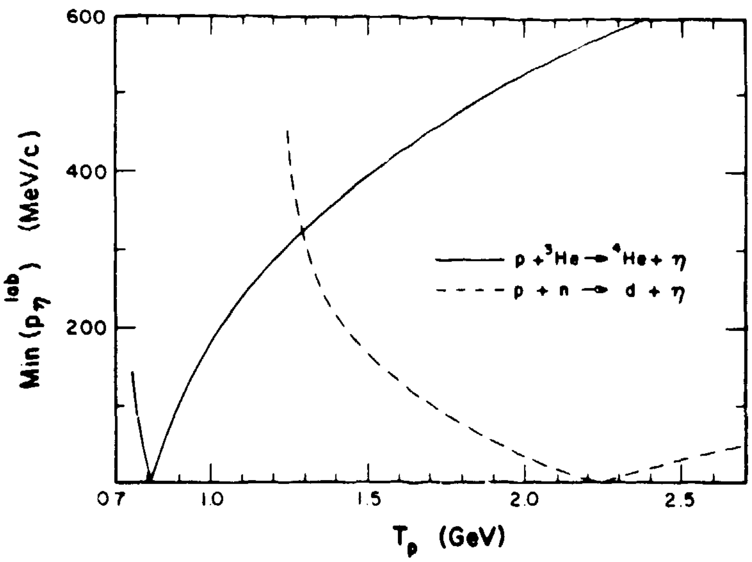

Fig.5 The lowest η momenta produced in the p+n → d+η and p+³He → ⁴He+η reactions as a function of proton kinetic energy.

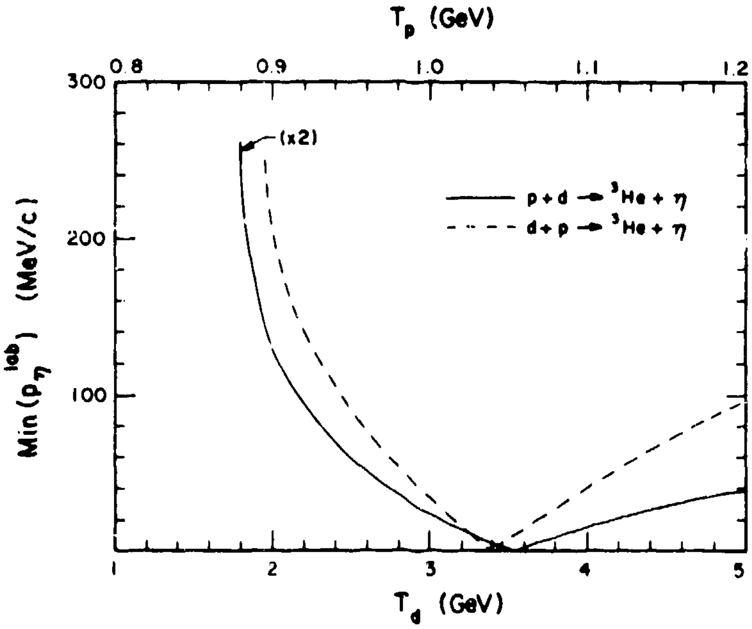

Fig.6 The lowest η momenta produced in the p+d → ³He+η and d+p → ³He+η reactions as a function of proton (upper abscissa) and deutron (lower abscissa) kinetic energies, respectively.

The existence of a zero-momentum of η in Figs.5 and 6 indicates that the inclusive (p,d), (p,^{4}He), (p,^{3}He), (d,^{3}He) reactions on medium-mass nuclei and at appropriate energies are ideal to the search for η-mesic nuclei as well as to the study of low-energy ηN interaction.

SUMMARY AND PERSPECTIVES

I have discussed the possibility of producing η-mesic nuclei by the use of pions. If these nuclei are observed experimentally, then the binding energies of the η in this new nuclear matter can be used to extract accurately the ηNN^* coupling constant in a nucleus.

Although I did not have time to discuss in detail various other interesting aspects of η's in nuclei, I would like to mention two of them:

(a) Because the basic $\pi N \to \eta N$ reaction is dominated by a spin nonflip interaction, the (π,η) reaction represents an excellent tool to study $\Delta T=1$ and $\Delta S=0$ nuclear transitions;

(b) The existence of η-mesic nucleus can lead to a new class of nuclear phenomena, η-mesic compound-nucleus resonances.(Details can be found in Ref.8.) An awareness of this phenomenon could be beneficial to the analysis of nuclear reactions at energies above the η production threshold.

Finally, I would like to emphasize that a very broad scope of new physics can be brought into place by studying η mesons in nuclei, and such studies require only a modest upgrading of existing meson facilities.

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